SHEAR BOND STRENGTH OF BRACKET BASES TO ADHESIVES BASED ON BRACKET BASE DESIGN

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DEDICATION

This thesis and research is dedicated to my family. The support I receive from them and the values and ethics I've learned from them are my motivation to keep moving in the right direction. And to my wife, Allyson, I'm forever grateful for your patience and support, enabling me to pursue dreams as we begin to build our life together. The joy I receive from these key players in life provide the energy needed to be persistent and focused. Last and most importantly, I would like give thanks to my Lord and Savior Jesus Christ for helping me to keep my path straight and showing me the way in this residency and beyond.

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“The best teacher is not the one who knows most but the one who is most capable of reducing knowledge to that simple compound of the obvious and wonderful.”

— H.L. Mencken

ABSTRACT

Intro: There were two specific aims of this study. The first aim was to show that the testing method developed is without investigator bias. The second aim was to test the difference in bond strengths at the bracket base-adhesive interface. It was hypothesized that new retentive design features in bracket bases would provide a higher shear bond value when compared to the traditional mesh based orthodontic bracket.

Methods: The experimental design included 4 test groups, each consisting of different bracket base designs. Group 1 included 3M Unitek's Victory Series ™ with Mesh Pad. Group 2 included ODP's Comfort Zone ™ Series with Anchor Lock™ Pad consisting of retentive pylons with undercuts (Claiming bond strength equal to or greater than conventional mesh pads). Group 3 included ODP's Comfort Zone ™ Series with Accu-Lock ™ Mesh Pad. Group 4 included Dentaurum's M Series ™ with Laser Structured Base (Claiming bond strength twice that of mesh bases). Each group was mounted on a jig compatible with the Instron® Universal Testing Machine #5543 (Instron®, Norwood, MA). Shear bond strengths were obtained in Megapascals (MPa) calculated from the peak load of failure in Newtons (N) divided by the specimen surface area. The Adhesive Remnant Index (ARI) was used to assess the amount of resin left on the bracket base after debonding. A double blind method was used to prevent operator bias when assigning ARI scores.

Results: The most retentive bracket bases proved to be Dentaurum's M Series ™ with Laser Structured Base followed by 3M Unitek's Victory Series ™ with Mesh Pad, ODP's Comfort Zone ™ Series with Anchor Lock™ Pad, and finally ODP's Comfort Zone ™ Series with Accu-Lock ™ Mesh Pad.

Statistical analysis included one-way ANOVA with Tukey's HSD analysis which allowed us to determine if there was a significant difference among the sample groups of shear bond values. Once found, a pairwise comparisons between bracket groups was possible. The Kruskal-Wallis test allowed us to determine if there was a significant difference between sample groups in relation to ARI scores. The Mann-Whitney test between each possible pair of sample groups revealed precisely which sample groups were significantly similar and which were significantly different.

These analyses displayed statistical significant differences between some bracket groups at the .05 level of significance. These results both reject and support our null hypothesis when looking at different bracket groups within our study.

Conclusions: Within the parameters of this study design, the results support that retentive design features do affect the shear bond strengths of orthodontic brackets. However, some manufacturer's (who produce brackets other than traditional mesh pads) claims of shear bond strength equal to or greater than conventional mesh pads were not supported in this study.

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I. BACKGROUND AND LITERATURE REVIEW

The method of applying force to teeth has been evolving since ancient times. An important standard of quality care critical for orthodontics is to be efficient in the length of treatment time while specific treatment goals are met (Andrews, 1972). Adhering to and meeting these ideals have in many ways defined the success of the profession. For this to happen, the apparatus to which forces can be applied to each tooth has become vitally important. One of the specific limiting factors of delivering precise force at the correct time has been in the attachment apparatus to each individual tooth through which forces may be applied. Through diligent research efforts, clinical experience, and trial and error, this attachment apparatus to teeth has evolved. A brief look at history shows an evolution of different ways that force has been applied to teeth from teeth tied to cat gut wrapped around crude metal bands found on mummified ancients, to advanced adhesive systems applied to precision machined metal brackets and bonded to the enamel surface. This latest and currently practiced technique of direct bonding of metal orthodontic brackets to natural teeth has been an accepted technique since introduced by Newman in 1965. Bond strength values ranging from 6-8 MPa for composite resin cements were originally reported. The development of a bonding technique is a result of the increased requirements needed in modern orthodontic tooth movement. Original tooth movement evolved from simple movements limited to tipping in pre-Angle days, to more complex three dimensional movements including torque, translation, intrusion and extrusion in Angle and post Angle eras. As a result, the strength and precision of systems to apply forces through teeth have also been refined as a requirement to meet these complex tooth movements.

To achieve the complex tooth movements demanded during modern comprehensive orthodontic therapy, the orthodontic clinician requires a reliable method of attachment to tooth tissue (Knox, Hubsch, Jones, and Middleton, et al., 2000). It's important for this component of the orthodontic appliance to provide reliability over time so that clinician's focus may be better appropriated to the specific treatment mechanics of each individual case. The reverse, however, may result in deleterious effects from appliance debond. The failure of this attachment results in interruption to patient treatment and can pose a potential hazard to the airway, damage to adjacent teeth, extended treatment time, and consumption of the treating orthodontist's resources (Zachrisson, 1985).

Biological forces are applied to the teeth through daily function of the oral cavity. These forces are combined with additional forces detrimental to the attachment apparatus such as undesirable habits like fingernail biting. Combined, these overtones quickly allow the practitioner to realize the importance of consistent and reliable attachment of the bracket to tooth surface. As brackets are stressed by orthodontic forces and masticatory loads, a high bonding performance is required, but the brackets have to be easily removed at the end of treatment with no compromise in the underlying structure of natural tooth (Wang *et al*., 2004). One study reported that enamel fracture can occur with bond strengths as low as 13.5MPa which was comparable to the linear tensile strength of the enamel (Retief 1975). Adhesion to teeth, accidental debonding of brackets, and damage to the enamel surface have motivated investigation of these problems (Sorel et al., 2002) according to different variables such as adhesive material, design of the base, type of pre-treatment, method of debonding, and curing technique (Merone et al., 2010).

When focusing more specifically on the bracket-cement interface, the advent of adhesive bracket bonding has led to a myriad of adhesive systems and bracket base designs. Both of these play an important role in bracket-tooth bonding strengths which have two planes of interface. One plane is the cement-enamel and the other is the cement-bracket. Current methods of bond strength evaluation test the cohesive strength of the cement and the strength of bracket-cement and cement-enamel interfaces, recording only the weakest element of this system. The ideal plane of failure remains between the bracket-cement because this limits potential damage to the tooth structure. Modern bonding strengths at the cement-tooth interface may exceed the value at which enamel fractures typically occur during debonding at 20-25 MPa (Cal-Neto et al., 2006, Chen et al., 2008, Kitahara-ceia et al., 2008). Therefore, it is important to keep the bond failure at the cement-bracket interface. By keeping the cement-bracket bond failures below the critical 20-25 MPa, we can minimize enamel fracture.

The morphology of the bracket base is an important variable for the retention of a bracket (Knox et al., 2001). Most brackets bases do not chemically bond to enamel or resin. Instead, bracket bases incorporate various types of retentive features in their intaglio surface to aid in retention. This type of retention is strictly mechanical in nature. These authors suggested that the base design may improve penetration of the adhesive material. The interface of bracket to cement has historically been highlighted through mechanical undercuts. Stainless steel brackets remain the most commonly used in the market, although ceramic and plastic brackets continue to be introduced and refined (Proffit, 1986). Reynolds and von Fraunhofer (1977) emphasized that stainless steel gauze bases provided better retention than perforated metal bases. Also, R. Maijer and

D.C. Smith (1981) corroborated these findings by showing the gold standard of the bracket to adhesive interface has been through a mesh base bracket. Brackets comparable to Orthodontic Design and Production's (ODP) single cast bracket with retention pylons have been tested to consistently display inferior bond strengths when compared to the traditional mesh bases. (Sharma-Sayal 2003, Regan 1989, Diedrich and Dickmeiss 1983)

Studies in bond strength have taken many different forms. Standards have been established over the years as to what constitutes clinically acceptable results. 5.9-7.8MPa is the range of bonding strength that is clinically acceptable for performing orthodontics (Reynolds 1975). Modern orthodontic shear bond strength studies generally report bond strengths in the range of 8-12MPa (Bishara 2004). Also, when determining the types of debonding tests to perform, shear/peel methods of testing are more appropriate to the clinical situation vs. tensile. Shear/peel methods of testing more closely represent the physiologic forces under which intra-oral debonding occurs. (Tavas and Watts 1979, Regan 1989). An additional evaluation often used in the critique of bond failures is the Adhesive Remnant Index System which allows the tester to determine the quality and location of bond failure (Montasser, 2009). In this indexing system, the plane of failure is observed under microscope and a general mode of failure is then reported according to the amount of adhesive left on the bracket compared to the surface of the substrate.

Recent research and development have resulted in the production of various bracket base designs other than the traditional mesh bases for reasons to include easier methods of manufacture and production, more cost effective development, and a continued strive for achieving the perfect union of orthodontic appliance to tooth surface with minimal debond rates. One of the latest bracket base designs has been offered by ODP's state of the art Anchor-Lock ™ Pad which claims to take bonding to a whole new level. With this bracket, the base and bracket is cast as one integral unit and the base features miniature pylons that function like sturdy anchors embedded firmly into the adhesive. The claim is that this design provides one of the strongest bonds available in the orthodontic market (ODP Webiste). This concept is not new however. Ferguson (1984) did a study on bracket base comparisons with a bracket called the Dyna-Lock by 3M Unitek, which also featured similar components of mechanical undercuts with the retentive pylons. Findings resulted in the integral base to perform relatively poorly with a "no-mix" adhesive and the bracket has since been discontinued. Other studies which point out inferior performance of the integral bracket bases when compared to mesh bases include Cozza (2006) who states that 80G mesh foil seems to be the most retentive design of retentive bases. An also notable observation was that single and double mesh bracket bases have comparable shear bond strength and bracket failure modes (Bishara 2004), indicating that double mesh bracket bases offer no clinically significant advantage over single mesh bases. Nonetheless, even the integral brackets provided acceptable bond force levels at the base/adhesive interface.

Finally, one other company on the market with a unique bracket base design claims that it provides the best bond retention on the market, guaranteed. Dentaurum also manufactures a one-piece integral bracket with a laser structured base instead of the previously mentioned mesh or pylon base for retention. This base has a uniform distribution of micro and macro retention which creates an ideal bond for each bracket. There are no other alloys or solder used during production of Dentaurum brackets. These new design features of bracket bases, in addition to their claimed equal or superior bond strengths with traditional mesh bases, become important in both clinical orthodontics and also in the production, design, and marketing of orthodontic products. The manufacturing of a one piece integral bracket base design with retentive features is faster and more cost effective to produce, and this is seen most easily in the cost comparisons on the respective ordering forms. The difficulty lies within the product confidence of the practicing clinician. If the clinician does not have faith in the bond strength of this more cost effective design, the product will not become a success and traditional mesh bases will continue to predominate. On the contrary, if it can be proven than these new integral brackets are clinically acceptable, with bond strengths equal to or greater than the traditional mesh bases, the production of these integral bases will become more popular. As a result of this clinical acceptance in the integral bases, clinicians may be able to appreciate a financial savings passed on by the savings in production costs to the manufacturers.

The purpose of the present study is to compare the strength of the bracket/adhesive interface, using one of the most clinically accepted adhesive systems, Transbond XT ™ by 3M Unitek, between a traditional single layer mesh bracket, ODP's precision located mesh base bracket, Dentaurum's laser-structured base, and ODP's single cast bracket featuring the Anchor –Lock ™ Pad representing the integral bracket base design.

II. OBJECTIVES

A. Overall Objective

The overall goal of this study is to determine the effect of different bracket base designs on the interfacial shear bond strength between the orthodontic bracket base and the adhesive used to adhere the bracket to the tooth surface.

B. Specific Hypothesis

It is hypothesized that advances in bracket base design will increase the bond strength between bracket base and adhesive over traditional mesh based brackets.

III. MATERIALS AND METHODS

A. Experimental Design

Because we are concerned in the bond between the bracket base and the adhesive in this study, the design of the testing system is focused on ensuring that fracture takes place at this interface as far as possible. Machine milled stainless steel cylinders will be used for the substrate in this test, but modified before use (Figure 1). A recessed concavity with retentive undercuts will be milled in the cylinder for each bracket tested. The base of this cavity will be made more retentive by milling an undercut in the base to create additional retention for the composite. Transbond XT ™ (3M Unitek) will be placed in each cavity and made flush with the milled surface of the stainless steel cylinder before curing (Figure 2). A mylar strip will be placed over each Transbond XT ™ filled cavity to ensure consistency in surface texture with minimum excess flash outside of the milled cavity (Figure 3,4). Light curing will be completed with a VALO ™ (ULTRADENT, SOUTH JORDAN, UT) curing light (Figure 5). The VALO ™ (ULTRADENT, SOUTH JORDAN, UT) curing light is a light emitting diode producing high intensity light at 395-480nm. The setting will be set to Plasma mode with a power level of 4500mW. A dental curing light photometer by BlueLight Analytics (HALIFAX, NOVA SCOTIA, CANADA) will be used to ensure standardization of the emitted wavelengths from the VALO ™ (ULTRADENT, SOUTH JORDAN, UT) curing light to 1300mW/cm^2. The Transbond XT ™ base will be cured for 3 seconds. The mylar strip will be removed and brackets to be tested immediately loaded with Transbond XT ™ and pressed onto the center of the prepared Transbond XT ™ bases of the stainless steel cylinder. Bracket position will be verified with the use of a bracket position measuring gage from measurement lines milled into the stainless steel cylinder substrate (Figure 6). Any excess Transbond XT ™ will be removed with probe before curing. Each bracket will be cured for 3 seconds on each of 4 sides.

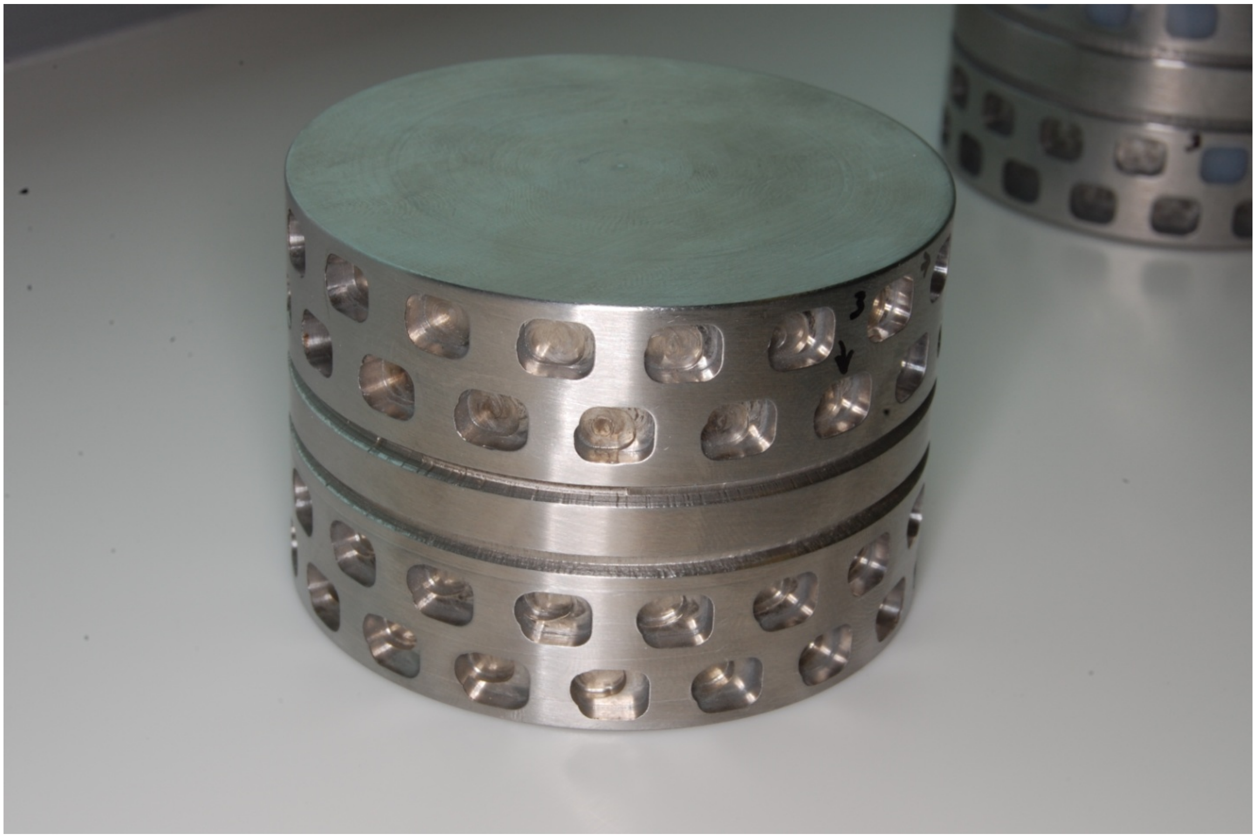


Figure 1: Machine milled stainless steel jig used to mount brackets.

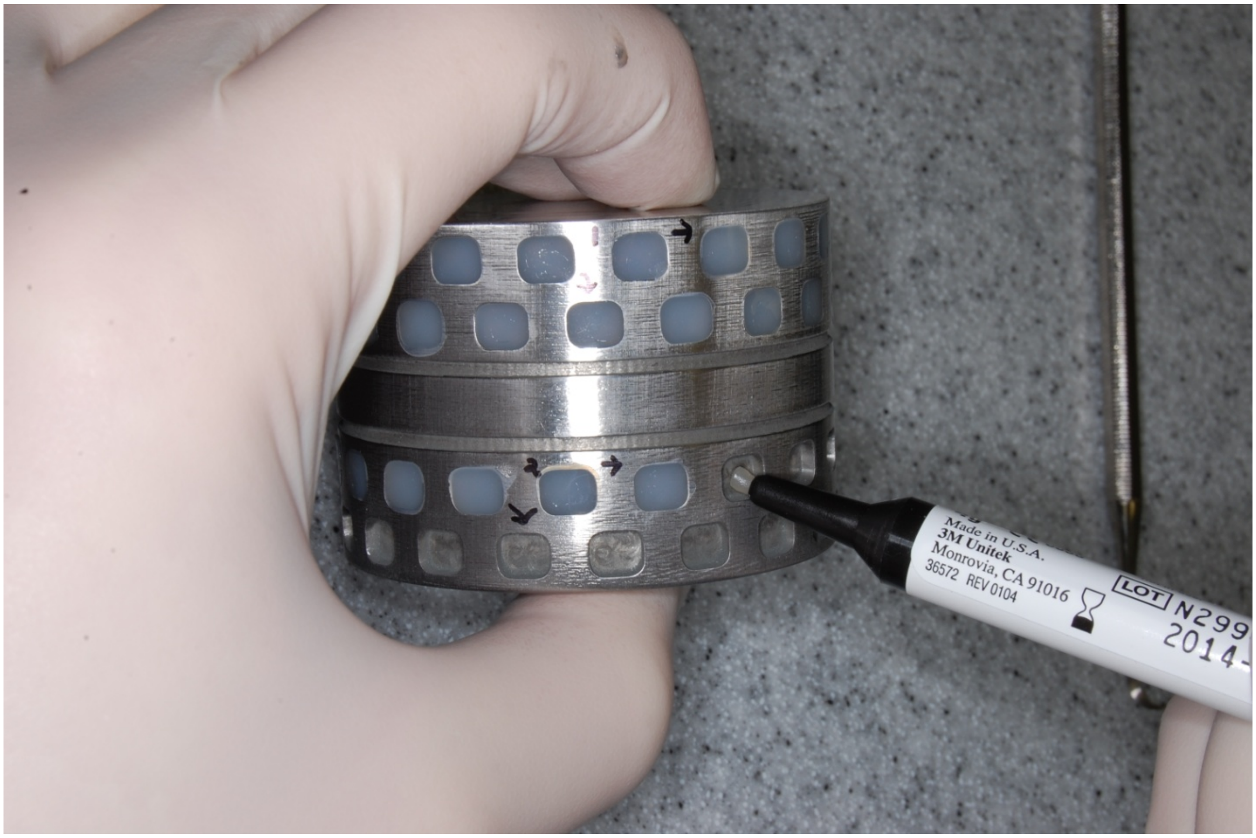


Figure 2: Substrate of Transbond XT ^{TM} (3M Unitek) being applied into the milled concavities of the jig.

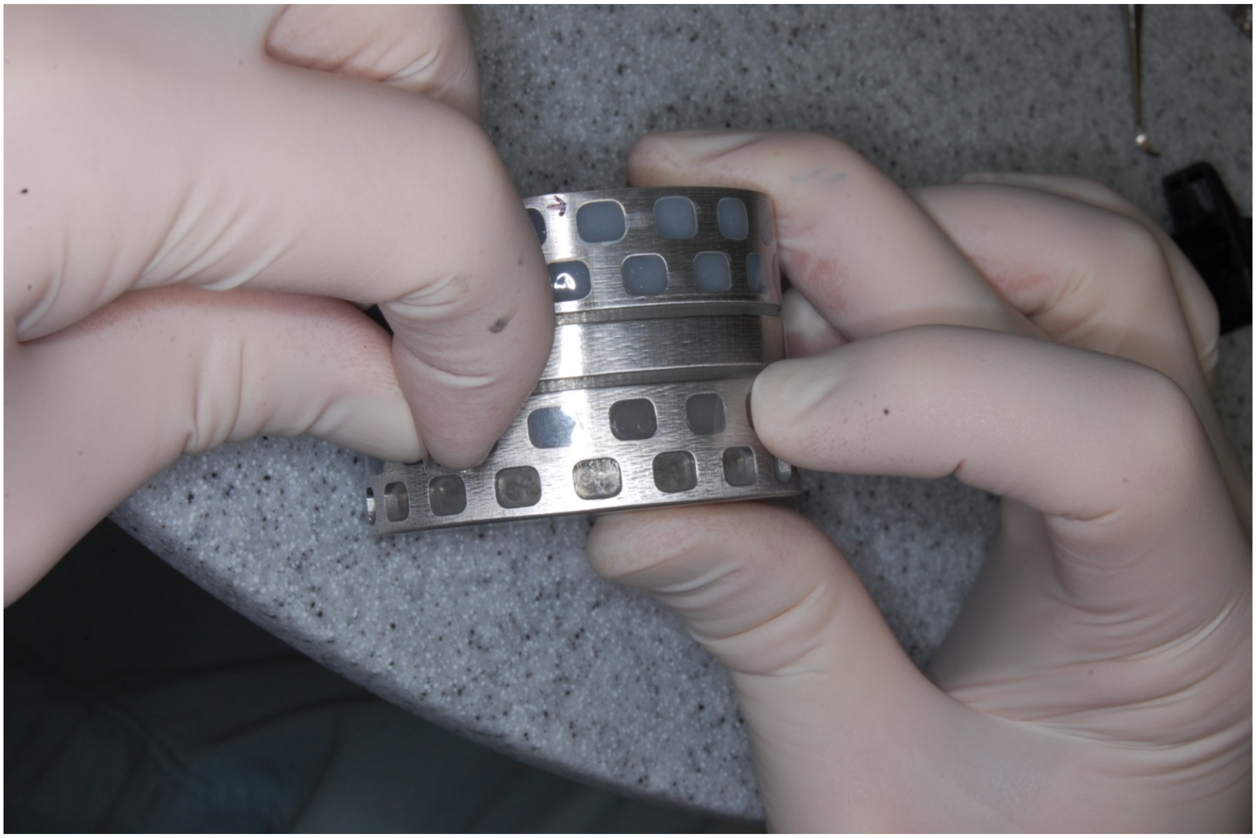


Figure 3: Mylar strip placed over each Transbond XT ™ filled cavity to ensure consistency in surface texture.

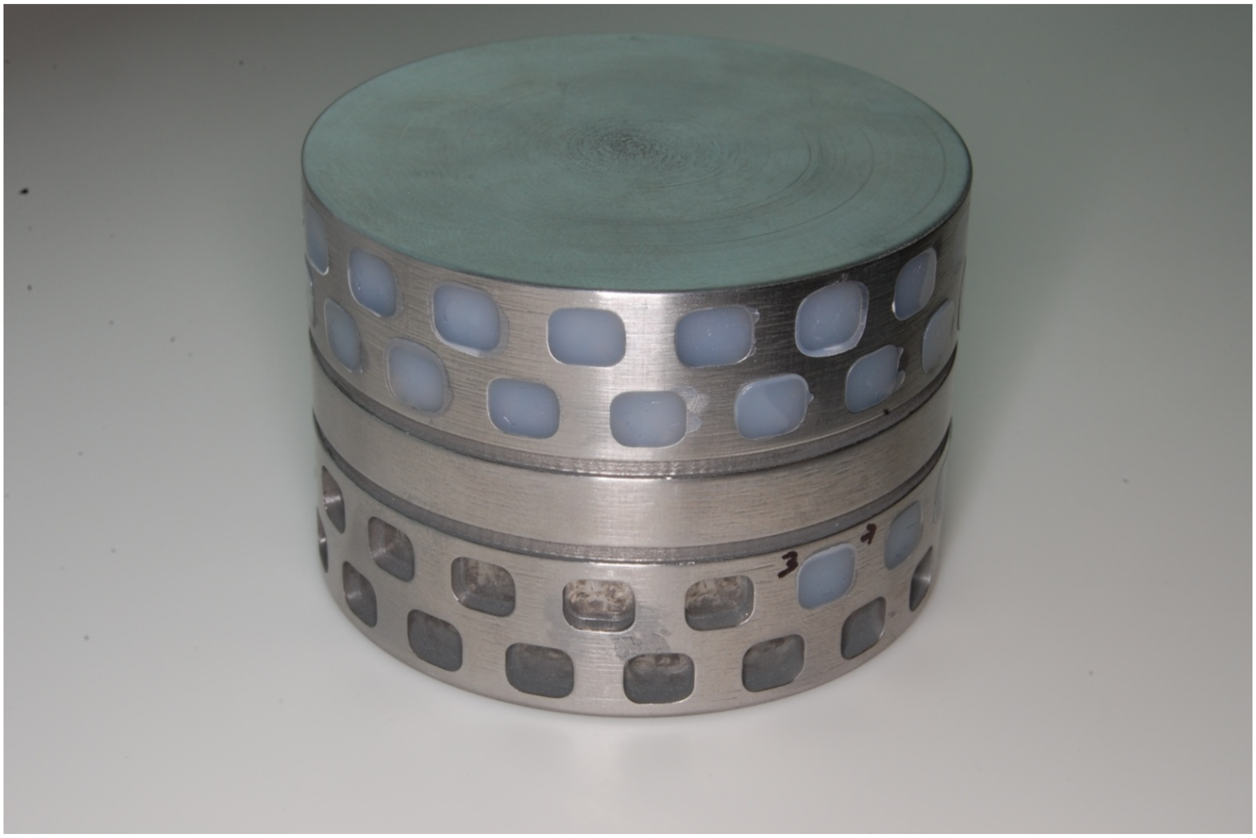


Figure 4: Cured substrate on top two rows of jig (minimal flash) ready to receive bracket placement.

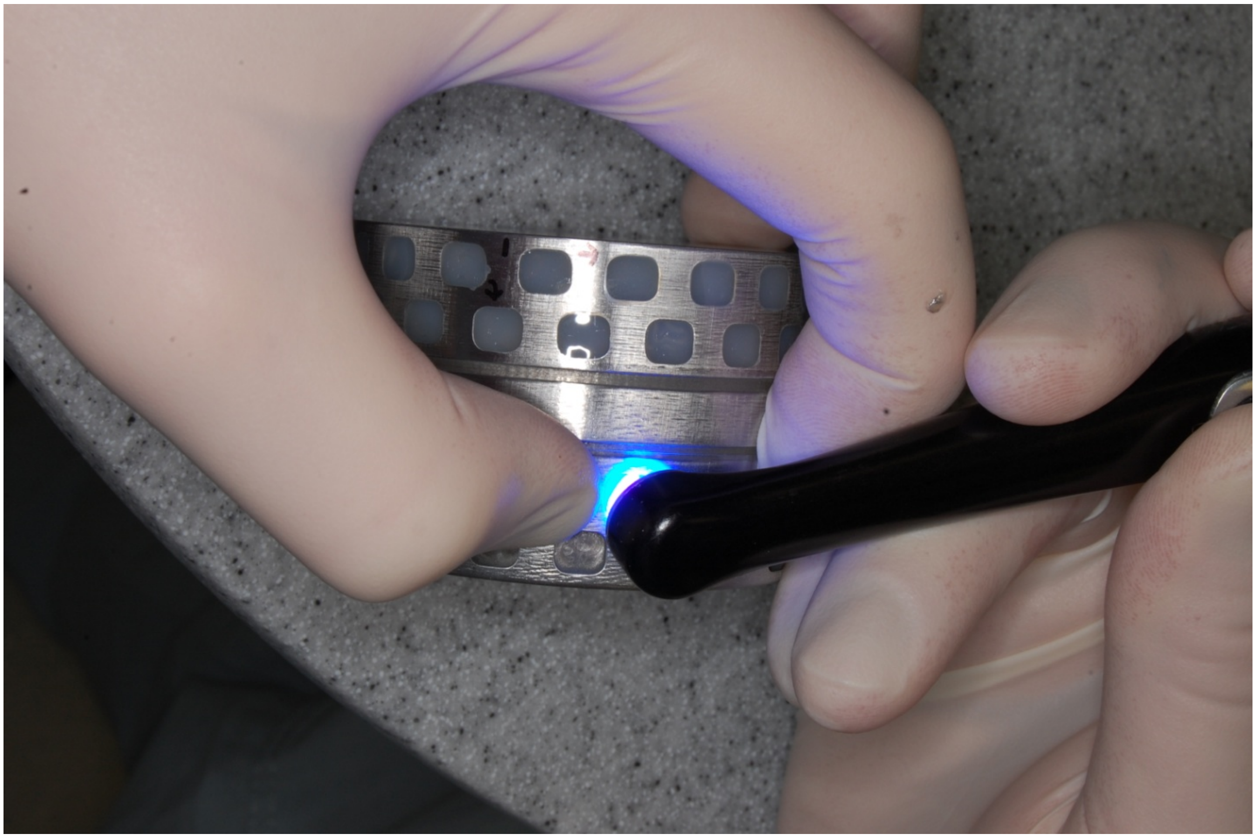


Figure 5: Light curing with a VALO TM (3M UNITEK, MONROVIA, CA) curing light.

Figure 6: Bracket position verified with the use of a bracket position measuring gage from measurement lines milled into the stainless steel cylinder substrate.

The adhesive used (Transbond XT ™ by 3M Unitek) is in accordance with the manufacturer's instructions and applied to the base of each bracket. To ensure consistency, all brackets to be used will be 00 degrees prescription brackets (Figure 7,8,9,10). Sample groups are categorized according to the brackets used. Four different styles of brackets will be used resulting in 4 sample groups.

Group 1: 3M Unitek's Victory Series ™ with Mesh Pad

Group 2: Orthodontic Design and Production's (ODP) Comfort Zone ™ Series with Anchor Lock™ Pad

Group 3: ODP's Comfort Zone ™ Series with Accu-Lock ™ Mesh Pad

Group 4: Dentaurum's M Series ™ with Laser Structured Base (Claiming bond strength twice that of mesh bases)

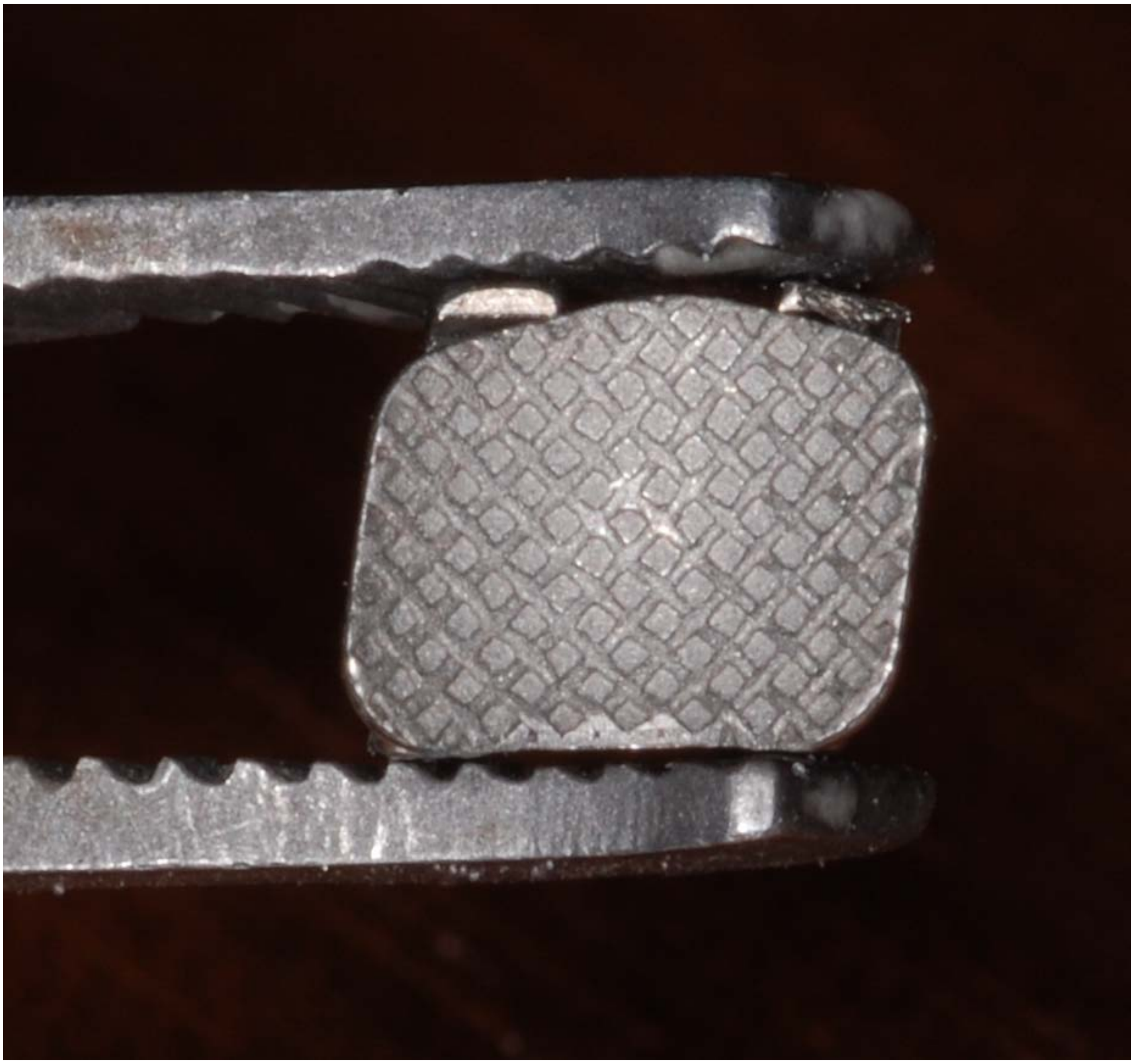


Figure 7: 3M Unitek's Victory Series ^{TM} with Mesh Pad.

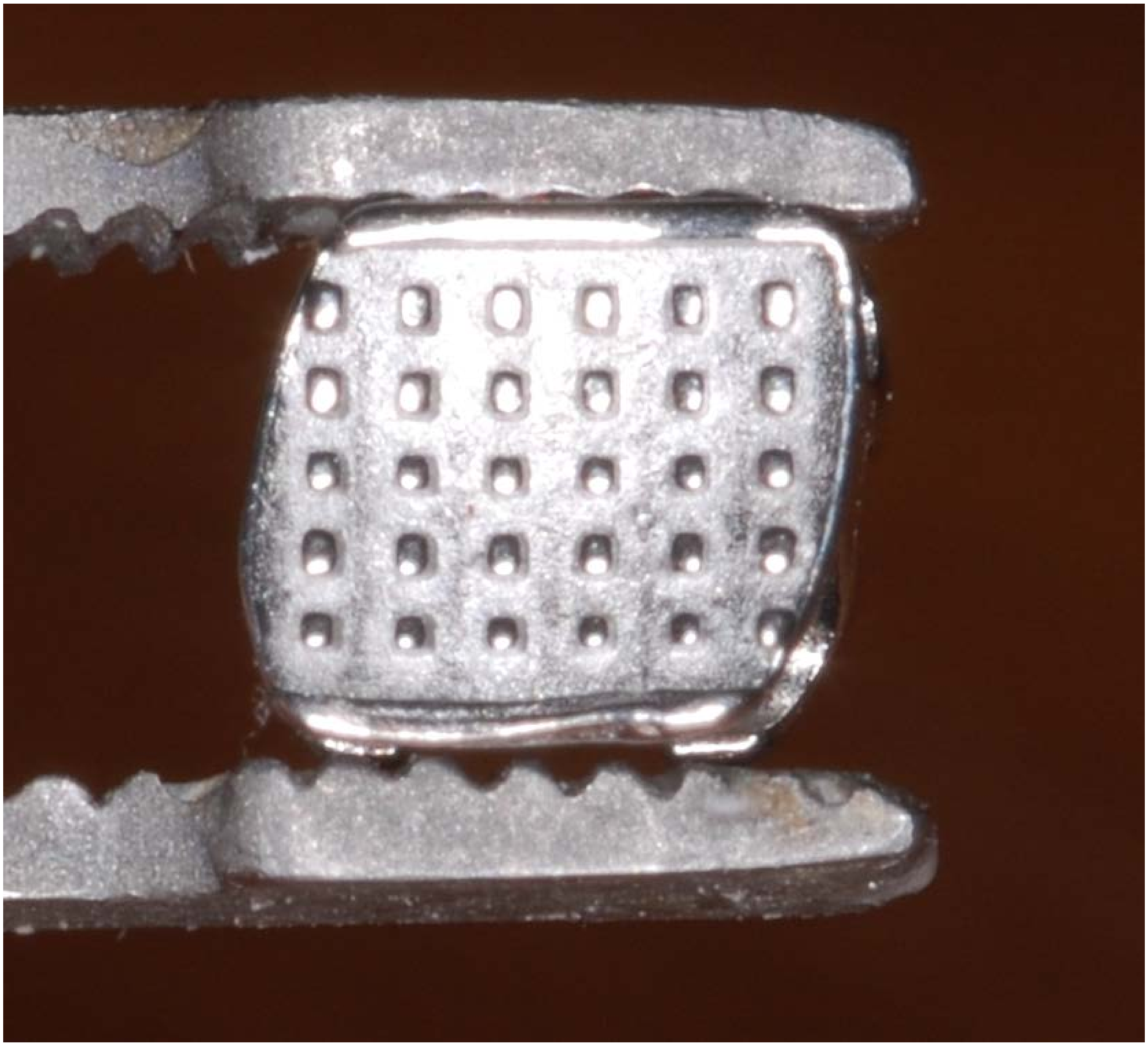


Figure 8: ODP's Comfort Zone ™ Series with Anchor-Lock ™ Pad.

Figure 9: ODP's Comfort Zone ™ Series with Accu-Lock ™ Mesh Pad.

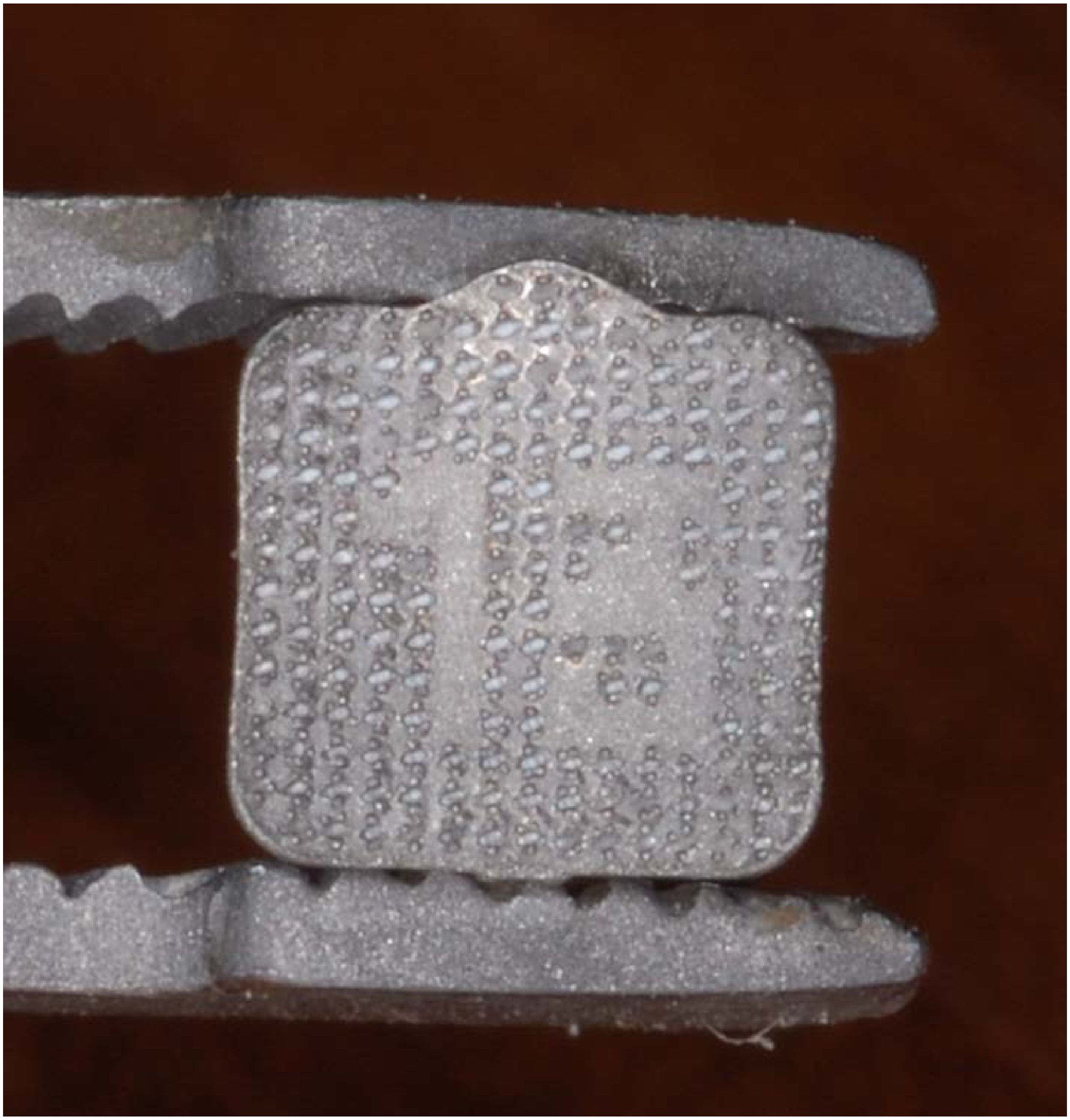


Figure 10: Dentaurum's M Series ™ with laser structured base.

A total of 100 brackets will be tested consisting of 25 brackets per sample group. A universal testing machine by Instron® (Norwood, MA) will be used to perform the debonding shear tests. These tests will be performed by using a single blade engaging the bracket behind the superior bracket wings (Figure 11). The crosshead speed will be 1mm/min and the force required to debond the brackets will be recorded. Shear bond values in Megapascals (MPa) will be calculated from the peak load of failure (in Newtons) divided by the specimen surface area (Table 1,2). After testing, each bracket base will be examined under a Nikon stereo microscope SNZ-1B (Nikon Instruments, Melville, NY) to determine the predominant site of fracture (Figure 12). This is classified as bracket/adhesive, within the adhesive, or adhesive/substrate.

Force per unit area will be calculated in the bracket base for each sample group to standardize debonding forces across the groups.

The Adhesive Remnant Index (ARI) will be used to evaluate the amount of adhesive left on the bracket base after debonding to establish the sites of adhesive fracture. Brackets are observed with magnification using the Nikon SNZ-1B at 10X magnification (Nikon Instruments, Melville, NY), and the adhesive remaining is scored with respect to the amount of resin material remaining: ARI 0, no adhesive remained on the bracket base with a clear and distinct impression of the bracket base on the substrate; ARI 1, less than half of the adhesive remained on the bracket base; ARI 2, more than half of the adhesive remained on the bracket base; ARI 3, all of the adhesive remained on the bracket base (Table 3).

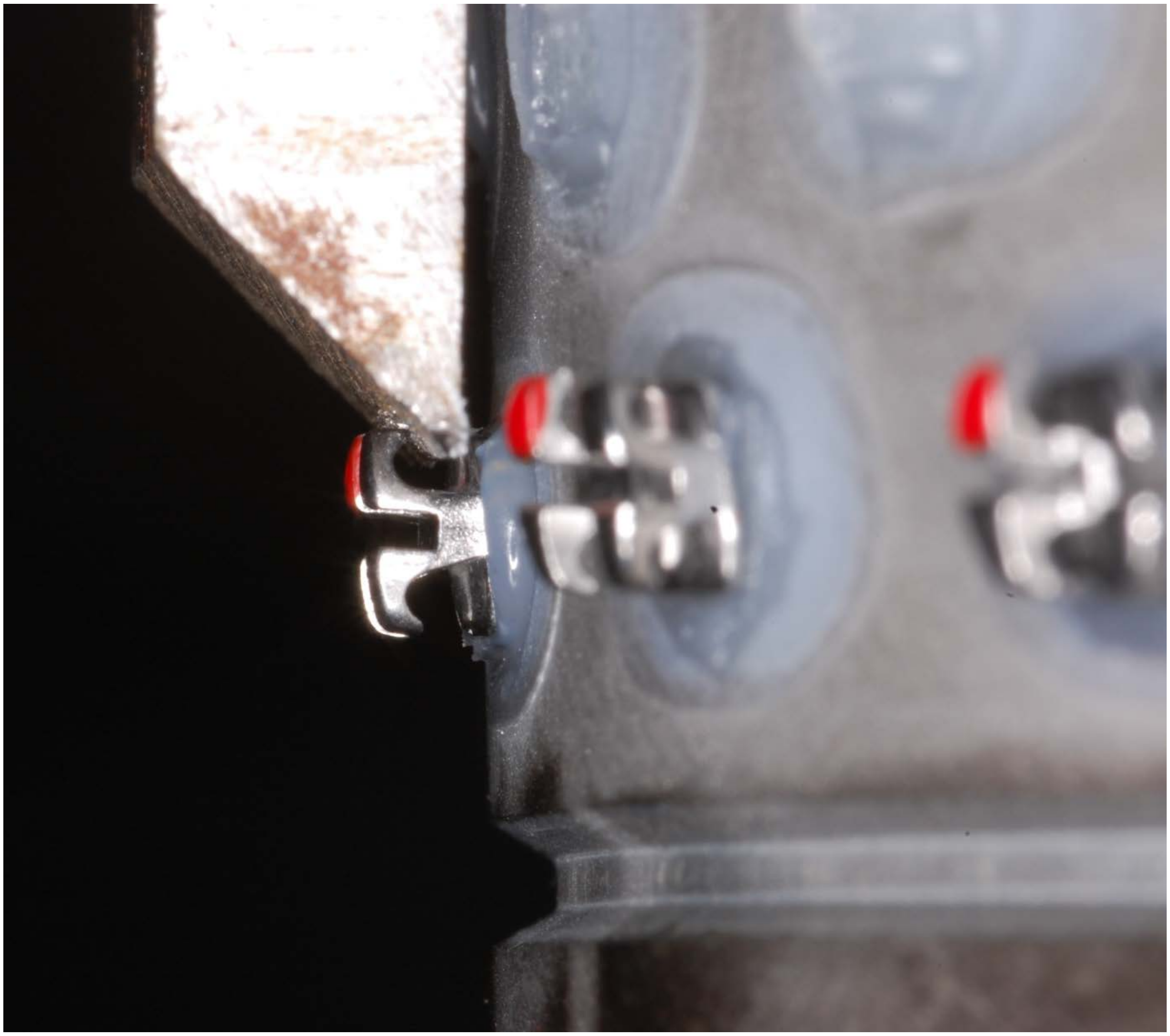


Figure 11: Blade connected to Instron® Universal Testing Machine #5543 (Instron®, Norwood, MA) and engaging orthodontic bracket behind the superior bracket wings.

Table 1: Shear bond values in Megapascals (MPa) calculated from the peak load of failure in Newtons (N) divided by the specimen surface area.

Group 1		Group 2		Group 3		Group 4	
Load at Max Load (kN)	MPa	(kN)	MPa	(kN)	MPa	(kN)	MPa
74.531	7.31	24.158	1.29	75.027	2.98	30.939	2.88
21.676	2.13	52.030	2.77	58.608	2.33	134.042	12.48
51.548	5.06	54.110	2.88	59.403	2.36	53.325	4.97
69.308	6.80	76.330	4.07	11.418	0.45	172.061	16.02
61.978	6.08	74.313	3.96	47.644	1.90	46.467	4.33
26.461	2.60	68.829	3.67	56.665	2.25	110.714	10.31
19.502	1.91	52.945	2.82	22.414	0.89	74.552	6.94
43.151	4.23	97.582	5.20	44.975	1.79	35.140	3.27
60.650	5.95	46.058	2.45	56.457	2.25	40.489	3.77
32.083	3.15	41.544	2.21	47.689	1.90	180.791	16.83
47.055	4.62	28.736	1.53	31.742	1.26	101.708	9.47
50.694	4.97	89.541	4.77	38.103	1.52	125.246	11.66
55.110	5.41	54.505	2.90	29.422	0.81	28.355	2.64
46.315	4.55	18.504	0.99	19.155	0.76	139.318	12.97
39.649	3.89	39.624	2.11	20.495	0.82	62.132	5.79
48.150	4.73	60.378	3.22	63.365	2.52	100.003	9.31
45.251	4.44	43.596	2.32	31.176	1.24	100.489	9.36
75.242	7.38	28.376	1.51	92.251	3.67	59.888	5.58
50.851	4.99	43.263	2.30	66.123	2.63	35.765	3.33
62.435	6.13	13.194	0.70	60.371	2.40	48.824	4.55
51.931	5.10	47.504	2.53	81.885	3.26	145.153	13.52
42.203	4.14	57.533	3.07	32.576	1.30	147.691	13.75
60.469	5.93	26.836	1.43	55.026	2.19	137.269	12.78
41.392	4.06	55.814	2.97	75.160	2.99	169.597	15.79
13.212	1.30	61.604	3.28	64.395	2.56	78.353	7.30
Mean/Mean per unit area	4.67		2.68		1.96		8.78
St Dev/St Dev per unit area	1.59		1.12		0.92		4.60

Table 2: Specimen surface area according to group

Base area of each bracket group		
Group 1	10.19 mm^2	0.0158 in^2
Group 2	18.77 mm^2	.029088 in^2
Group 3	25.14 mm^2	0.038974 in^2
Group 4	10.74 mm^2	0.016647 in^2

Table 3: ARI Calibration Table

ARI Legend	
0	No adhesive on bracket base
1	Less than ½ bracket base covered in adhesive
2	More than ½ bracket base covered in adhesive
3	All adhesive remained on bracket base

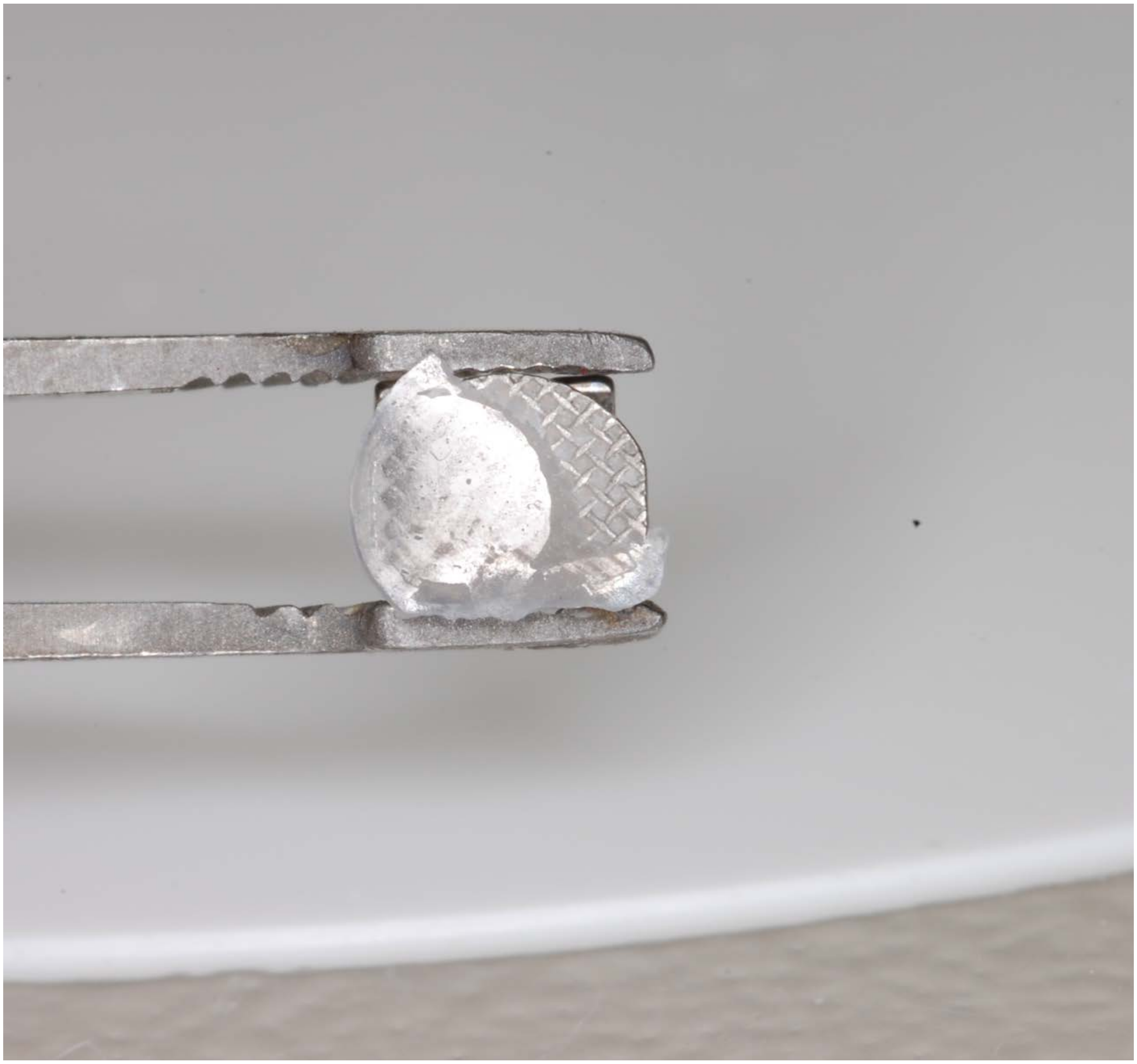


Figure 12: Debonded bracket held over viewing table of Nikon microscope SNZ-1B at 10X magnification revealing mode of bond failure in preparation of ARI scoring.

B. Statistical Management of Data

Descriptive statistics consisted of calculating the mean and standard deviation for each of the four bracket groups in megapascals (MPa) and Newtons (N). This was possible from the data collection which gathered shear bond strengths from the Instron® Universal Testing Machine #5543 (Instron®, Norwood, MA) in Newtons and divided this number by the surface area of each bracket.

In addition, adhesive remnant index (ARI) scores were collected for each bracket of each sample group. This data was organized into a chart, according to predetermined ARI scoring values (Table 3), where we could easily see the predominant mode of failure for each shear bond site (Figure 12).

Statistical analysis included a one-way analysis of variance (ANOVA) which was carried out to determine if the shear bond strength (SBS) protocol was reproducible and independent of the investigators. The ANOVA allowed us to determine if there was a significant difference among the sample groups. Once a significant difference was found, we applied Tukey's HSD post hoc test to screen for pair wise comparisons between bracket groups. This allowed us to determine between which bracket groups the difference was found. Our level of significance was defined when $p<.05$.

In reference to our ARI scores, we utilized the Kruskal-Wallis test to determine if there was a significant difference between sample groups. Like our use of ANOVA, when we found there was a difference, we ran the Mann-Whitney test between each possible pair of sample groups to find precisely which sample groups were significantly similar and which were significantly different to each other at the $p<.05$ confidence interval.

The sample size of 25 per group provided 80% power to detect a moderate effect size of 0.43 or approximately 0.86 standard deviation difference among means when testing with a single factor ANOVA at the alpha level of 0.05 (NCSS PASS 2002).

IV. RESULTS

The representative descriptive statistics for our study are as follows: Each bracket was debonded using the Universal Testing Machine (Instron® #5543). All shear bond strengths were converted to megapascals (MPa) by dividing the force in Newtons by the mean base surface area of orthodontic bracket type (Table 2). The raw shear bond strengths of the four groups are presented in Table I and summarized in Table 4. As can be appreciated in the table 1 and 4, the mean MPa (N/mm2) for the 4 groups ranged from the strongest (8.78 MPa) to weakest (1.96 MPa) in the following sequence: Group 4 > Group 1 > Group 2> Group 3.

The rough ARI results are displayed in Table 5 and broken down into percentages per sample group in Table 6.

The one way ANOVA test showed that there were statistically significant differences among the four groups with respect to shear bond strength ($p<0.001$) when referencing the tests of between –subject effects. Application of Tukey's post hoc test showed that Group 4 presented significantly greater shear bond strength in comparison with the other samples in Table 7 (95% confidence interval with $p<0.05$). Table 7 displays a significant difference between Group 4 and all the other groups. Group 1 was not significantly different than Group 2 and Group 2 was not significantly different than group 3. Otherwise, the remaining inter-group comparisons all remained significantly different.

The mode of failure was examined and an Adhesive Remnant Index (ARI) score was given to each sample group (Table 3,5). Due to the variability of the measurements within the group, a non-parametric test (Kruskal-Wallis with Mann-

Whitney) at a p>0.005 was used. Two possible types of fracture were observed: cohesive fracture, within the body of the cement; and adhesive fracture, at the cement-bracket base. For all the brackets, over 60% of failure was cohesive (Table 8). Group 1 and 4 showed a cohesive failure of greater than 80%. These two groups also displayed the highest shear bond values. Groups 2 and 3 displayed the only failure at cement-bracket base. These later two groups also displayed the lowest shear bond values. Group 3 displayed the highest variability of failure modes and also retained the lowest shear bond values across our study.   These results support our previous findings in Table 7 with relation to shear bond strengths because Group 2 and Group 3 are not significantly different in both Tables 7 and 8. Also, Group 1 and 4 which yield the highest shear bond strengths also are similar in their mode of failure seen in table 8.

Table 4: Descriptive Statistics (Shear bond in MPa)

Group	Mean	Std. Deviation	N
1	4.4968	1.8465	25
2	2.6780	1.1205	25
3	1.9644	0.9175	25
4	8.7840	4.5968	25

Table 5: ARI Scores

	Group 1		Group 2		Group 3		Group 4	
Number								
1	2		1		3		3	
2	3		3		3		3	
3	3		3		3		2	
4	3		2		1		3	
5	3		1		3		3	
6	3		3		3		3	
7	3		3		3		3	
8	3		3		3		3	
9	3		2		3		3	
10	3		3		1		3	
11	2		3		1		2	
12	3		3		2		3	
13	3		2		3		3	
14	3		3		1		3	
15	3		3		2		3	
16	3		3		1		3	
17	3		3		3		3	
18	3		3		3		3	
19	2		2		3		3	
20	3		2		3		3	
21	3		2		3		3	
22	3		3		2		3	
23	3		2		3		3	
24	3		3		3		3	
25	3		3		2		3	
Mean								
	2.88		2.56		2.44		2.92	

Table 6: ARI % Per Sample Group

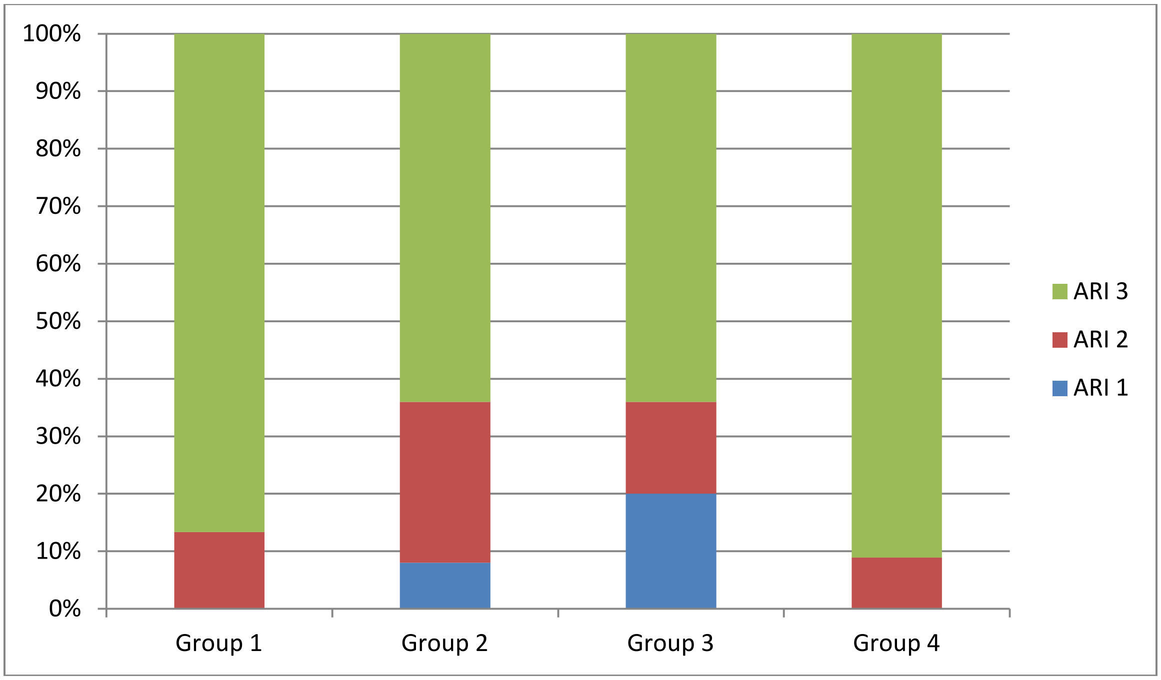


Table 7: Multiple Comparisons
Dependent Variable: MPa
Tukey HSD

Group	MPa (Std. Deviation)		
1	4.4968 (1.8465)	a	3M Unitek's Victory Series ™ Mesh
2	2.6780 (1.1205)	a b	ODP's Anchor Lock™ Pad
3	1.9644 (0.9175)	b	ODP's Accu-Lock ™ Mesh Pad
4	8.7840 (3.6877)		Dentaurum's Laser Structured Base

(Groups with the same letter are not significantly different p<0.05)

Table 8: Multiple Comparisons
Dependent Variable: ARI Score
Mann-Whitney

Group	ARI Score		
1	2.88	a	3M Unitek's Victory Series ™ Mesh
2	2.56	b	ODP's Anchor Lock™ Pad
3	2.44	b	ODP's Accu-Lock ™ Mesh Pad
4	2.92	a	Dentaurum's Laser Structured Base

(Groups with the same letter are not significantly different p<0.05)

V. DISCUSSION

Achieving adequate clinical bond strength is important when moving teeth orthodontically (Maijer et al, 1981). The stainless steel brackets used in our study obtain adequate clinical bond strength through mechanical retention, since they do not produce a chemical bond with adhesive materials. In this study our focus was on the design of the bracket base retentive features. Therefore, the material of the bracket base was controlled and limited to stainless steel. This allows us to focus strictly on the design of the bracket base and not include material variables. A review of the current literature reveals that orthodontic bracket bonding involves 3 materials and 2 interfaces. These three materials (enamel, cement, and orthodontic bracket base) have 3 interfaces of bond failure locations; at the bracket base, at the tooth surface, or within the cement. The ideal plane of failure remains between the bracket base/cement interface or entirely within the cement because this limits potential damage to the tooth structure. Once debonded, the remaining cement left on the tooth surface can then be safely removed with a finishing bur.

According to Retief, enamel fracture can be observed with shear bond strengths in the range of 13 MPa and above. In this study, the mean shear bond strengths between all 4 groups ranged from 1.96 MPa for Group 3 to 8.78 MPa for Group 4. Therefore, none of the shear bond values in this study showed a risk towards enamel fracture. The purpose of this study was to show which retentive features on bracket bases resulted in the highest shear bond values and still remained below the 13MPa threshold and within the envelope of safety in preventing enamel fractures.

In our study, Groups 1 and 3 were multi-piece brackets where the retentive mesh base was separate from the bracket and welded together during the manufacturing process. The brackets in group 2 and 4 were considered integral brackets in which the body and retentive base are a unique piece.

Group 1 (Figure 13) presents with 80-G mesh foil base claimed by studies such as Cozza (2006) who states that 80G mesh foil seems to be the most retentive design of retentive bases.

Group 2 (Figure 14) presents with an Anchor Lock™ Pad. This retentive base is characterized with pylons that extend vertically from the base of the bracket which creates channels where cement can flow and lock into for retention once cured.

Group 3 (Figure 15) presents with an Accu-Lock ™ Mesh Pad similar to Group 1 with a mesh pad that fits precisely into a metal frame cast on the base of the bracket.

Group 4 (Figure 16) is characterized by a laser-structured base in which the retention is obtained with many hole-shaped cavities on the bottom of the brackets that are realized by a laser beam scanned over the base surface. The laser beam preparation of this surface results in projecting metallic margins around the hole-shaped cavities.

To compare the retention capacity of brackets selected, it is necessary to express the shear bond strength in Newtons (N) and the bonding force in Megapascals (MPa). The values in Newtons describe the shear bond strength considering the retentive base surface, while the values in Megapascals (obtained by dividing the values in Newtons for the base areas) exclude the influence of the millimetric extension of the base and reflect strictly the effectiveness of the retention mechanism.

As previously stated, failure modes were consistent in relationship to shear bond values. On all the groups, the main mode of failure was within the Transbond XT ™ cement, resulting in a cohesive failure. This contrasts to an adhesive failure where the site of location is between the bracket base and Transbond XT ™ cement. A direct correlation exists between bond strength and failure mode. This finding corroborates our data. Group 4 with the highest mean shear bond value (MPa) had the highest cohesive failure rate (within the adhesive cement), while Group 3 had the highest adhesive failure rate (at the bracket base) and also displayed the lowest mean shear bond value (MPa). As the ARI scores increase in value from 1-3, it signifies a more cohesive failure rate, meaning within the adhesive cement. This corresponds to a higher shear bond value. If the failure rate is entirely within the cement, we see that the retention of the bracket base was high. Therefore, the bracket base/cement interface is the weakest link. This is supported in our study because those bracket bases which had higher failures at the bracket base/cement interface displayed the lowest shear bond values (Group 3).

When evaluating the difference in shear bond values between our sample groups, several explanations show why the results came out the way they did. For example, Groups 1 and 3 both characterize mesh bases and therefore would be thought to have similar shear bond values. The contrary, however, is true and to a statistically significant level. One explanation of this is due to surface preparation. The surface of Group 1 has mechanically micro-etched bases whereas the surface of Group 3 has EDM (Electrical Discharge Machining) prepared bases. EDM prepared bases utilize electrodes with electrical currents to micro-etch a material. One pitfall of EDM is the possibility of incomplete etching where removal of the debris from the inter-electrode volume is likely to be partial. This may result in certain portions remaining un-etched. On the other hand, Group 1 undergoes a mechanical micro-etching process that claims to uniformly etch the entire surface of the bracket pad resulting in increased retention. The difference in surface preparation of these two groups of brackets can be seen visibly when comparing Figures 7 and 9. When viewing Figure 9, the EDM preparation results in a shinier surface when compared to the mechanically micro-etched bracket in Figure 7. Another difference between the two groups involves the periphery of the bases. Group 1 displays an intimate contact of mesh with tooth surface allowing only the adhesive to remain between the two surfaces. The design in Group 3 includes a beveled chamfer which adapts around the mesh pad framing it in place. This metal “frame” around the mesh pad in Group 3 may prevent an ideal contour and incorporate interference between the mesh pad and tooth surface.

Group 2 had the most unique retentive features with its retentive pylons and had shear bond values that fell between Group 1 and Group 3. Because the design characteristics of both Group 2 and Group 4 were individually unique to our study, we did not have comparisons with similarly designed brackets. Notable, however, is how well Group 2 performed in the overall study compared with the “gold standard” of Group 1. The differences in results were not statistically significant and the strength of Group 2 may lie in the unique design of the surface area with mechanically designed retentive channels or pylons.

The clear winner in the sense of shear bond strength of this study is Group 4. This group displayed statistically significant shear bond values much greater than all the remaining groups. Several explanations persist for this finding starting with the increased surface area due to the laser etched base. Through laser etching, both micro and macroscopic retention is possible. Macroscopic surface etching is visible much like the bases of the previous three groups. However, microscopic holes are also perforated through the base which allows the adhesive to penetrate the base and form tags on the opposite side of the brackets intaglio surface. This has several effects. First, the tags increase mechanical retention by locking into the top side of the bracket base. As a result, there is a realized increase in surface area not initially calculated from the intaglio surface.

Clinical shear bond strengths needed for orthodontic brackets were reported by Raynold and fell into the range of 6-8 MPa. Although not all of our sample groups displayed these means, the failure modes were consistent in relationship to shear bond values. Also, this is an in vitro study and care should be taken in extrapolating the results to those that might be obtained in the oral environment. In fact, the aim of this study was to determine the retention capacity without considering in vivo real conditions.

In evaluating possible explanations of lower than clinically acceptable shear bond values in our study; we focused on several areas, with our substructure being the first. In an in vivo environment, enamel serves as the substructure for bonding orthodontic brackets. Our in vitro study utilized a cured block of Transbond XT ™ composite resin with minimal filler particles. This in vitro substructure is significantly thicker in dimension than when in the clinical setting and also less rigid than enamel. Therefore we had an increased flexural range of substructure during the shear bond testing. As a result, this presents the opportunity for increased variability of debond values and a decreased shear bond mean value with the possibility of a more widespread standard deviation. Also, a phase break was identified at debond sites between our substructure surface and the adhesive surface on the bracket bases. This was not evident in our pilot study and may indicate a weakness in material and methods. To eliminate this weak link, it may be recommended to cure the substrate and bracket base together in one curing step resulting in one solid block of adhesive with the bracket attached. This would eliminate any possible surface contamination during the bonding of brackets to substrate. An alternative method would be to micro etch the surface of the substrate before bonding the bracket to it. This additional step was performed in subsequent studies and showed more consistent and promising results with a significant decrease in standard deviation of shear bond values when looking within the same sample groups.

An additional area of weakness may lie upon the surface of our substrate. Because we used a cylinder that approximated the curvature of the bracket bases, the union was still an estimate and not precisely calculated to match the curvature of each bracket. Therefore, there was certainly uneven thicknesses of adhesive on different locations of each bracket base even after the brackets were pressed firmly to express any additional cement. Because the manufacturing process engineers bracket bases to fit specific shapes of tooth curvature, eliminating dead space filled with excess adhesive, error may be incorporated when not adhering to these principles. A solution to this variability could include a similar study with actual extracted human or bovine teeth to reproduce more accurately that bonding surface each bracket was designed for.

Figure 13: Two Piece Bracket with entire base welded to bracket wings.

3M Unitek's Victory Series ^{TM} with Mesh Pad

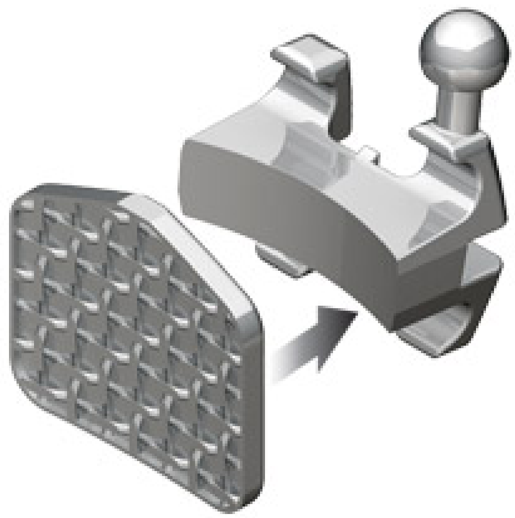


Figure 14: Integral Bracket with pylons that extend vertically from the base.

ODP's Comfort Zone ^{TM} Series with Anchor-Lock ^{TM} Pa

Figure 15: Two Piece Bracket with mesh retentive base welded into metal frame of bracket pad.

ODP's Comfort Zone ™ Series with Accu-Lock ™ Mesh Pad

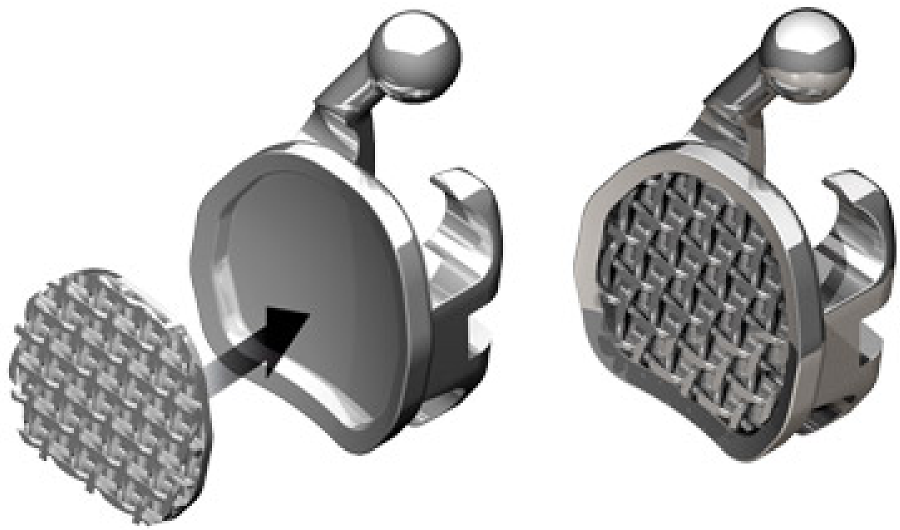
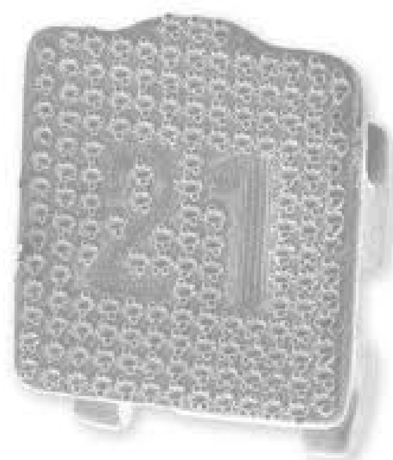


Figure 16: Integral Bracket with laser structured base.

Dentaurum's M Series ™ with laser structured base



VII. CONCLUSIONS

Within the parameters of this study, the following conclusions can be drawn:

1. Shear bond strength correlates directly with mode of failure in reference to the ARI Index. The higher the shear bond value, the higher the ARI score, with failure occurring within the cement resulting in cohesive failure.
2. Certain advances in bracket base design will increase the bond strength between bracket base and adhesive over traditional mesh based brackets. Laser structured bases (Group 4) offer the greatest shear bond values followed by mechanically micro etched mesh bases (Group 1). Next is integral pylon manufactured bases with retentive undercuts (Group 2) followed by mesh bases that have been prepared through EDM (Electrical Discharge Machining, Group 3).
3. Integral brackets, which often incur less expense in the production and manufacturing process compared with two-piece bracket systems, do have the possibility of shear bond values exceeding those of traditional mesh based brackets from both a clinically and statistically significant platform. As a result, clinically superior brackets may now be manufactured utilizing fewer steps and fewer pieces. This results in reduce areas of manufacturing error occur, improved precision, and reduced overall costs to the consumer.

FUTURE RESEARCH

When metal bracket bases are debonded, the site of failure occurs predominately at the adhesive-base interface. This failure site is independent of the type of bracket base design. There are several different treatments of bracket bases which can improve bond strength and potentially reduce the number of failures at the adhesive-base interface. These treatments include sandblasting, silanating, silicoating, etching, surface activation, sintering, and adhesive precoating. Testing these surface treatments on the various base designs against their respective control bracket may result in worthy comparisons in a clinical setting.

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